

# Signals for Supersymmetry at HERA

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## Abstract

We consider the baryon parity signals at HERA for the case of the MSSM production mechanisms and the decays via the lepton number violating couplings  $L_i Q \bar{D}$ . We can probe very small Yukawa couplings  $\lambda' \gtrsim 3 \cdot 10^{-6}$ , limited only by the decay length of the LSP. We assume the LSP to be the lightest neutralino and study its decays in detail. We present the matrix element squared for the tree-level decay amplitude of a generally mixed neutralino explicitly. We find that the branching fraction to charged leptons strongly depends on the SUSY parameters and can differ significantly from the naively expected 50%. The SUSY mass reaches of the studied processes in the ZEUS detector at HERA were found to be:  $(m(\tilde{e}, \tilde{\nu}) + m(\tilde{q})) \leq 170 \text{ GeV}$ ,  $195 \text{ GeV}$  and  $205 \text{ GeV}$  for the  $L_\tau Q \bar{D}$ ,  $L_\mu Q \bar{D}$  and  $L_e Q \bar{D}$  couplings respectively. These are well above existing limits on R-parity violating ( $R_p$ ) SUSY from previous experiments. We conclude that HERA offers a *very promising* discovery potential for  $R_p$  SUSY.

# 1 Introduction

When extending the Standard Model to include supersymmetry [1] the superpotential contains terms which lead to unsuppressed proton decay. The most elegant and economic solution to this problem is to impose a discrete symmetry which disallows the dangerous  $\Delta B \neq 0$  terms. Several discrete symmetries have been proposed, with R-parity ( $R_p$ ) [1] and Baryon Parity ( $B_p$ ) [2, 3] being the most common. Imposing  $R_p$  results in the minimal supersymmetric standard model (MSSM); in the case of  $B_p$  the superpotential contains the following lepton number violating terms beyond those of the MSSM [4, 2]

$$\lambda'_{ijk} L_i Q_j \bar{D}_k, \quad \lambda_{ijk} L_i L_j \bar{E}_k. \quad (1)$$

$L, Q$  denote the left-handed lepton- and quark-doublets, respectively;  $\bar{E}, \bar{D}$  denote the electron and down-like quark singlets respectively.  $\lambda, \lambda'$  are Yukawa couplings and  $i, j, k = 1, \dots, 3$  are generation indices. Theoretically it is still an unresolved question which is the preferred or proper symmetry.<sup>1</sup> Presumably it will be determined from the embedding of the supersymmetric standard model in a more fundamental theory at a higher energy scale. In fact, recent work in this direction hints at  $B_p$  being the preferred symmetry [5].

In light of this theoretical dilemma we propose to consider the full phenomenological possibilities, in particular to include the  $B_p$  signals in all supersymmetric searches. There is a growing amount of work in this direction for searches at hadron colliders [6]-[11] and at  $e^+e^-$ -colliders [12, 13] though clearly significantly less than for  $R_p$ .

In this paper we focus on promising  $B_p$  signals at HERA. HERA is particularly sensitive to the first operator in Eq.(1) since it couples to both leptons and quarks. When including a substantial coupling  $\lambda'_{ijk}$  the phenomenology changes in two main respects: (1) resonant squark production is possible at substantial rates; (2) the lightest supersymmetric particle (LSP) is not stable and can decay in the detector.

Resonant squark production at HERA has been considered in [14, 15] and was studied in detail in [16, 17], where cascade decays of the squarks to the LSP have been included. The squark mass reach was found to be [17]

$$m_{\tilde{q}} \leq 270 \text{ GeV} \quad \text{for} \quad \lambda' \geq 0.08, \quad (2)$$

and the reach in the Yukawa coupling in this mode is

$$\lambda' \geq 5.3 \cdot 10^{-3} \quad \text{for} \quad m_{\tilde{q}} \simeq 100 \text{ GeV}. \quad (3)$$

In this paper we fully exploit the second possibility, the decay of the LSP. We consider the associate pair production of supersymmetric particles via supersymmetric gauge couplings

$$e^- + q \rightarrow \tilde{e}^- + \tilde{q}, \quad (4)$$

$$e^- + q \rightarrow \tilde{\nu} + \tilde{q}'. \quad (5)$$

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<sup>1</sup>Experimentally clearly no statement can be made since supersymmetry has not been found.

followed by the decay within the detector of the scalar fermions ( $\tilde{f} = \tilde{e}, \tilde{\nu}, \tilde{q}$ ) via the LSP to a  $R_p$ -even final state.<sup>2</sup> For example in the case of a dominant operator  $L_i Q_j \bar{D}_k$

$$\tilde{f} \rightarrow f + \tilde{\chi}_1^0 \rightarrow f + \{(e_i^\pm + u_j + \bar{d}_k) \text{ or } (\nu_i + d_j + \bar{d}_k)\}. \quad (6)$$

We have denoted the LSP by  $\tilde{\chi}_1^0$  the conventional notation for the lightest neutralino. The main signal for these events will then be a high  $p_T$  charged lepton.

The mechanisms (4,5) have been studied in detail in the context of  $R_p$ , where the dominant signals are missing  $p_T$  [18, 19, 20, 21]. These studies have generally lead to the conclusion that there is little discovery potential for supersymmetry at HERA beyond the limits set by the experiments at the Tevatron. In [16, 17] this was shown not to be the case if  $R_p$  is violated. One essential point of this paper is to provide further viable signals at HERA for the case of  $B_p$ .

In studying the  $B_p$  signals we go beyond previous work [16, 17, 8] in the following respects:

- The production cross sections (4,5) are independent of the Yukawa coupling. Thus it is possible to probe extremely small couplings, which are only limited by the requirement that the LSP decay within the detector, *i.e.*  $\lambda' \gtrsim 3 \cdot 10^{-6}$ . Recall, the smallest Yukawa coupling in the SM, the electron-Higgs coupling, is just of this order.
- Since the lepton number violating coupling is not involved in the production cross section, we are able to explore the full generation structure of the operator  $L_i Q_j \bar{D}_k$ . We must only require  $j \neq 3$  since a top quark in the final state is beyond the kinematic reach of HERA. In particular we can also study the  $L_\tau Q_j \bar{D}_k$  operator, which leads to a tau lepton in the final state.
- We have considered a general neutralino as the LSP (as opposed to restricting the study to a photino). This has two main effects in  $B_p$  studies. (1) For the operator  $LQ\bar{D}$  the branching fraction for the LSP decay to charged leptons very strongly depends on the mixing parameters of the neutralino sector. (2) For a dominantly Zino/Higgsino LSP and small LSP masses the decay rate (proportional to a SM Yukawa coupling squared) can become so small that the LSP does not decay within the detector. This severely limits the range of couplings that can be probed by the  $B_p$  high  $p_T$  charged lepton signals.
- We have included the charged current production mechanism (5). In  $R_p$  this is not very promising since it is difficult to distinguish from the SM charged current events. However, in  $B_p$  both the sneutrino and the squark decay via the LSP to predominantly visible final states. This increases the overall event rate by about a factor 2.5 [22].

The clear disadvantage of employing the mechanisms (4) and (5) is that the mass reach is severely restricted by the kinematic limit of HERA, since two sfermions must

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<sup>2</sup>The direct decay of the sfermions via the operator  $LQ\bar{D}$  is strongly suppressed for the small  $\lambda'_{ijk}$  we are considering. For a detailed discussion see [7, 11].

be produced. This corresponds directly to the problem encountered in the context of the MSSM. However, since we are now considering the case where the LSP *decays* the previous MSSM squark mass bounds derived mainly from searches for missing  $p_T$  signals at CDF must be reexamined. We discuss this in more detail below.

In our analysis we shall make the following simplifying assumptions

- (A1) We shall assume the LSP is a neutralino<sup>3</sup>. In some regions of the MSSM parameters the LSP is a chargino. We do not study these supersymmetry models.
- (A2) Of the 27 operators  $L_i Q_j \bar{D}_k$  we shall assume in turn that one operator dominates [7], and the others are negligible. We thus have 18 separate scenarios to consider ( $j \neq 3$ ).
- (A3) The cascade decay of the sfermions to the LSP is 100% of the branching fraction.

Our paper is outlined as follows. In Section 2 we summarise the relevant previously existing bounds on the  $B_p$  parameters. In Section 3 we review the work on the production mechanisms Eqs.(4,5). In Section 4 we present a detailed analysis of the LSP decays for the operator  $LQ\bar{D}$ . We focus on the branching fraction to charged leptons and on the decay length. Combining the last two sections we examine the signals, which we compare with possible backgrounds in Section 5. In Section 6 we formulate appropriate cuts to extract the signals. This is the core of the analysis. We discuss the results and conclude in Section 7.

## 2 Existing Bounds

The existing bounds on the operators  $\lambda'_{ijk} L_i Q_j \bar{D}_k$  are of two kinds: (a) indirect bounds from low-energy processes involving virtual supersymmetric particles; (b) direct bounds from collider searches. Both sets of bounds make the simplifying assumption (A2) of a single dominant  $\mathcal{R}_p$ -operator.

- (a) The most stringent relevant indirect bounds are [23]

$$\lambda'_{L_e Q_i \bar{D}_j} \leq \begin{cases} 0.06 \times \left[ \frac{\tilde{m}}{200 \text{ GeV}} \right], & i = 1, \\ 0.52 \times \left[ \frac{\tilde{m}}{200 \text{ GeV}} \right], & i = 2, 3 \end{cases} \quad (7)$$

$$\lambda'_{L_\mu Q_i \bar{D}_j} \leq \begin{cases} 0.18 \times \left[ \frac{\tilde{m}}{200 \text{ GeV}} \right], & i = 1, \\ 0.44 \times \left[ \frac{\tilde{m}}{200 \text{ GeV}} \right], & i = 2, 3. \end{cases} \quad (8)$$

Note that the bounds scale linearly in the relevant supersymmetric scalar fermion masses  $\tilde{m}$ . And there are **no** indirect bounds on the tau-operators  $L_\tau Q_i \bar{D}_j$ .

- (b) The most detailed collider bounds have been determined by D.P. Roy [8]. Here use is made of the CDF top-quark search which sets bounds on any di-lepton production beyond that of the SM. At the Tevatron, the MSSM pair production of squarks, followed by the  $\mathcal{R}_p$  cascade decay via the LSP would lead to a di-lepton signal. The bound on

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<sup>3</sup>This is a strong assumption, since the LSP is not stable and the bounds on relic densities of charged or coloured particles are no longer relevant.

the di-lepton production directly translates to a bound on the squark pair production cross section, which to a good approximation only depends on the squark masses. The bound on the squark masses thus obtained is

$$\tilde{m}_q \geq 100 \text{ GeV}, \quad L_e Q_i \bar{D}_j, L_\mu Q_i \bar{D}_j. \quad (9)$$

And again there is no bound for the tau operators. In addition there are model independent bounds from LEP, which hold for all operators [24]

$$\tilde{m}_e \geq 45 \text{ GeV}, \quad \tilde{m}_q \geq 45 \text{ GeV}. \quad (10)$$

Thus our best bounds are

$$\tilde{m}_e + \tilde{m}_q \geq \begin{cases} 145 \text{ GeV}, & L_{e,\mu} Q \bar{D}, \\ 90 \text{ GeV}, & L_\tau Q \bar{D}. \end{cases} \quad (11)$$

Besides studying SUSY bounds at HERA as opposed to the Tevatron, we differ from [8] in the following two important points. First, we consider a general neutralino LSP. This has a significant effect on the branching fractions of the LSP in the case of the operator<sup>4</sup>  $LQ\bar{D}$ . It can also have a significant effect on the lifetime, and thereby the decay length of the LSP. The reach in coupling constant in our analysis only depends on the decay length (see also Section 4.3). Second, we also consider the tau operator  $L_\tau Q \bar{D}$ . HERA has an inherently cleaner environment than the Tevatron and thus has a non-trivial discovery potential for  $L_\tau Q \bar{D}$ . Third, we consider *single* lepton signals and are thus less sensitive to model-dependent variations in the charged lepton branching fraction.

Further collider searches have been proposed for  $e^+e^-$  [13] and for hadron colliders [6, 10]. In particular [13] also does a detailed analysis of the tau-number violating operators for LEP200. They consider gaugino pair production which is complimentary to the dominant HERA signal. The signal at LEP200 is insensitive to the squark mass and depends on the slepton mass only via the propagator, however it strongly depends on the (neutralino) LSP mass.

### 3 Production Mechanism

The dominant  $R_p$  conserving SUSY production mechanisms at HERA are the Neutralino Current (NC) and Chargino Current (CC) processes of Figure 1. Here  $\tilde{\nu}$ ,  $\tilde{e}_{L,R}$  and  $\tilde{q}_{L,R}$  are the sneutrino, the left and right handed selectron and squark respectively. In the MSSM there are two pairs of charginos,  $\chi_{1,2}^\pm$ , and four neutralinos,  $\chi_{1..4}^0$ . Following the notation of Haber and Kane [1], masses and couplings depend on the parameters  $M'$  and  $M$  (the U(1) and SU(2) gaugino parameters), the Higgsino mass mixing parameter  $\mu$ , and  $\tan(\beta) = \frac{v_1}{v_2}$ , the ratio of the vacuum expectation values of the two Higgs doublets. We shall throughout assume the GUT relation [25]

$$M' = \frac{5}{3} \tan^2(\theta_W) M, \quad (12)$$

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<sup>4</sup>That the operator  $LQ\bar{D}$  is special in this respect was already pointed out in [16, 17].

where  $\theta_W$  is the electroweak mixing angle. Gaugino mixing has been thoroughly discussed in the literature, and we refer to [1, 19, 26] for details.

Processes (4) and (5) have been calculated by various authors [27, 28, 22]. As discussed in [29], the cross sections exhibit a strong dependence on the sum of the two final state SUSY particle masses,  $(m_{\tilde{e}} + m_{\tilde{q}})$  or  $(m_{\tilde{\nu}} + m_{\tilde{q}})$ . Furthermore they show some dependence on the gaugino mass parameter  $M'$ , but are relatively insensitive to the parameters  $\mu$  and  $\tan(\beta)$ . Figure 2 shows a contour plot of the SUSY cross section  $\sigma_{e+q \rightarrow \tilde{l}+\tilde{q}'}$  (where  $\tilde{l}$  can be a selectron or a sneutrino) as a function of  $M'$  and  $(m_{\tilde{l}} + m_{\tilde{q}})$ . The hatched region indicates where the mass of the lightest neutralino becomes larger than  $m_{\tilde{l}}$  and  $m_{\tilde{q}}$ , the masses of the scalars <sup>5</sup>. Since we have assumed the lightest neutralino to be the LSP, we do not consider this region of parameter space. Note that within the region of interest to HERA (scalar masses up to  $\sim 200 \text{ GeV}$ ) cross section variations as a function of  $M'$  are within a factor of two for  $M' > 10 \text{ GeV}$ . Figure 3 shows the number of expected events per  $200 \text{ pb}^{-1}$  (two nominal years of HERA running <sup>6</sup>) for a number of values  $M'$  and their corresponding LSP masses.

The produced (on-shell) selectrons, sneutrinos and squarks subsequently cascade-decay into lighter SUSY particles via (making use of assumption **(A3)** in Section 1)

$$\tilde{e}_{L,R}^- \rightarrow e^- + \tilde{\chi}_i^0 \quad (13)$$

$$\tilde{\nu} \rightarrow \nu + \tilde{\chi}_i^0 \quad (14)$$

$$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0. \quad (15)$$

Eventually only one type of SUSY particle remains, the LSP. In  $R_p$  conserving models the LSP escapes detection, and the resulting SUSY signals are  $e^- + 1jet +$  missing transverse momentum for the NC case, and  $1jet + \cancel{p}_T$  for the CC case. Several studies [21, 29] have concluded that HERA's eventual discovery reach on selectron, sneutrino and squark production for R-parity conserving MSSM SUSY is  $m_{\tilde{e}} + m_{\tilde{q}} < 200 \text{ GeV}$  and  $m_{\tilde{\nu}} + m_{\tilde{q}} < 180 \text{ GeV}$  at an integrated luminosity of  $200 \text{ pb}^{-1}$ .

In the following sections we shall concentrate on the decay of the LSP via  $R_p$  couplings, including the full neutralino mixing of the MSSM. We shall show that the squark mass discovery reach of the LQD operator is comparable to that of the R-parity conserving case, for a very wide range of Yukawa couplings.

## 4 LSP Decays

### 4.1 Matrix Element

Here we present the matrix element squared for the decay of the LSP via the operator  $L_i Q_j \bar{D}_k$  to the charged lepton final state. We consider a general neutralino LSP and we retain all final state fermion masses. Thus we also include the ‘‘higgsino’’-like couplings which are proportional to the fermion masses.

$$|\mathcal{M}(\tilde{\chi}_0 \rightarrow e_i u_j \bar{d}_k)|^2 = 8c_f g^2 \lambda_{ijk}^2 \{ \quad (16)$$

<sup>5</sup>Assuming  $\tilde{e}$ ,  $\tilde{\nu}$  and  $\tilde{q}$  to be degenerate in mass.

<sup>6</sup>Presently, prior to the 1994 running period, the integrated luminosity at HERA is  $1 \text{ pb}^{-1}$ .

$$\begin{aligned}
& D(\tilde{u}_j)^2 e_i \cdot d_k \quad [(a(u_j)^2 + b(u)^2) \tilde{\chi}_0 \cdot u_j + 2a(u_j)b(u)m_{u_j}M_{\tilde{\chi}_0}] \\
& + D(\tilde{d}_k)^2 e_i \cdot u_j \quad [(a(d_k)^2 + b(\bar{d})^2) \tilde{\chi}_0 \cdot d_k - 2a(d_k)b(\bar{d})m_{d_k}M_{\tilde{\chi}_0}] \\
& + D(\tilde{e}_j)^2 u_j \cdot d_k \quad [(a(e_i)^2 + b(e)^2) \tilde{\chi}_0 \cdot e_i + 2a(e_i)b(e)m_{e_i}M_{\tilde{\chi}_0}] \\
& - D(\tilde{e}_i)D(\tilde{u}_j) \quad [a(u_j)a(e_i)m_{e_i}m_{u_j}\tilde{\chi}_0 \cdot d_k + a(u_j)b(e)m_{u_j}M_{\tilde{\chi}_0}e_i \cdot d_k \\
& \quad + a(e_i)b(u)m_{e_i}M_{\tilde{\chi}_0}u_j \cdot d_k + b(e)b(u)g(u_j, \tilde{\chi}_0, e_i, d_k)] \\
& - D(\tilde{u}_j)D(\tilde{d}_k) \quad [a(u_j)a(d_k)m_{u_j}m_{d_k}\tilde{\chi}_0 \cdot e_i - a(u_j)b(\bar{d})m_{u_j}M_{\tilde{\chi}_0}e_i \cdot d_k \\
& \quad + a(d_k)b(u)m_{d_k}M_{\tilde{\chi}_0}e_i \cdot u_j - b(u)b(\bar{d})g(u_j, \tilde{\chi}_0, d_k, e_i)] \\
& - D(\tilde{e}_i)D(\tilde{d}_k) \quad [-a(e_i)b(\bar{d})m_{e_i}M_{\tilde{\chi}_0}u_j \cdot d_k + a(e_i)a(d_k)m_{e_i}m_{d_k}\tilde{\chi}_0 \cdot u_j \\
& \quad + a(d_k)b(e)m_{d_k}M_{\tilde{\chi}_0}e_i \cdot u_j - b(e)b(\bar{d})g(\tilde{\chi}_0, e_i, u_j, d_k)] \}
\end{aligned}$$

Here  $c_f = 3$  is the colour factor <sup>7</sup> and  $g$  is the weak coupling constant. We have denoted the 4-momenta of the initial and final state particles by their particle symbols. The functions  $D(p_i)$  denote the propagators squared for particle  $p$  and are given by

$$D(\tilde{p}_i)^{-1} = M_{\tilde{\chi}_0}^2 + m_{p_i}^2 - 2\tilde{\chi}_0 \cdot p_i - \tilde{m}_{p_i}^2. \quad (17)$$

The coupling constants  $a(p_i)$ ,  $b(p)$  are for example given in [30] and are listed in the Appendix for completeness.

The amplitude squared of the decay to the neutrino,  $\tilde{\chi}_0 \rightarrow \nu_i d_j \bar{d}_k$ , can be obtained from the above result by a set of simple transformations of the 4-momenta, the propagator functions  $D$  and the couplings  $a(p_i)$ ,  $b(p) : e_i \rightarrow \nu_i, u_j \rightarrow d_j$ . In order to determine the total decay rate these two modes must be integrated over phase space, added, and then multiplied by a factor of two, since the LSP is a Majorana fermion and can decay to the conjugate final states.

The result for the operators  $L_i L_j \bar{E}_k$  is completely analogous, except the colour factor  $c_f = 1$ . The result for the operators  $\bar{U} \bar{D} \bar{D}$  is given in the Appendix.

## 4.2 Charged Lepton Branching Fraction

Before discussing the results of the calculation in detail, we outline their general nature. We focus on the discussion of the LSP decays to  $\tau$ 's via the  $L_i Q_j \bar{D}_k$  operator ( $j \neq 3$ ). Branching fractions to  $e^\pm$  and  $\mu^\pm$  (via the operators  $L_e Q_j \bar{D}_k$  and  $L_\mu Q_j \bar{D}_k$  respectively) are within a few percent of the tau results. The only noticeable difference enters in the Higgsino region, where the LSP lifetime is larger for decays to electrons and muons than for decays to taus (by a factor  $(m_\tau/m_{e,\mu})^2$ ).

We have found that the branching fraction of the LSP decay to  $\tau$ 's and  $\nu_\tau$ 's strongly depends on the nature (i.e. the gaugino mixing parameters) of the LSP. The LSP decay falls into one of the following three distinctively different regions:

1. A region where the LSP predominantly decays to  $\tau$ 's. Branching fractions of the LSP in this region are typically  $\text{BF}(\chi_1^0 \rightarrow \tau^\pm + 2\text{jets}) \sim 70\%$ . Experimentally this

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<sup>7</sup>A simpler form of this result was obtained in Ref[17] for the case of a photino LSP and neglecting the final state fermion masses. The colour factor was omitted there by mistake. This error does not affect any of the results presented there since only branching fractions were employed, not the absolute decay rate.

region is the most interesting one, because the event topology contains an “exotic” lepton (the  $\tau$ ).

2. A region where the LSP predominantly decays to  $\nu_\tau$ 's. Branching fractions of the LSP in this region are typically  $\text{BF}(\chi_1^0 \rightarrow \nu_\tau + 2jets) \sim 85\%$ . One can still look for the signature of decays of the LSP to  $\tau$ 's, but the bounds are significantly weaker.
3. A region in which Higgsino/Zino contributions to the LSP become dominant and the LSP mass is small. In this region, the decay rate of the LSP can become so small that the LSP only decays within the detector for anomalously large couplings  $\lambda'$ . Thus the dominant signature would again be the missing  $p_T$  signal of the  $R_p$  conserving MSSM scenario. We will not consider this region in the subsequent Monte Carlo (MC) study.

The neutralinos are admixtures of their weak eigenstates  $\tilde{\gamma}$ ,  $\tilde{Z}$ ,  $\tilde{H}_1^0$  and  $\tilde{H}_2^0$ . If the LSP dominantly consists of the  $\tilde{\gamma}$  component, branching fractions to  $\tau^\pm$  are large, while a predominance of the  $\tilde{Z}$  component makes  $\chi_1^0 \rightarrow \nu_\tau + 2jets$  the more preferred decay channel. If the LSP is more Higgsino-like, the scenario gets more complicated as the branching fractions now also depend on both the vacuum expectation values of the SM Higgs and the mass of the decay leptons.

We shall now discuss the results of the LSP calculation in detail. The amount of mixing of  $\tilde{\gamma}$ ,  $\tilde{Z}$  and the two Higgsinos is determined by the SUSY parameters  $M'$ ,  $M$ ,  $\mu$  and  $\tan(\beta)$ . Assuming the GUT relation (12), we are left with the three “free” parameters  $M'$ ,  $\mu$  and  $\tan(\beta)$ . Figure 4 shows the resulting LSP decay regions as a function of the SUSY parameters for the dominant operator  $L_\tau Q \bar{D}$ . The white region indicates where  $m_{\chi_1^0} > m_{\chi_1^\pm}$ , the region where the mass of the lightest neutralino is greater than the mass of the lightest chargino. Since we have assumed that the LSP is a neutralino, we do not consider this region in parameter space. The branching fraction  $\text{BF}(\chi_1^0 \rightarrow \tau^\pm + 2jets)$  is less than 30% <sup>8</sup> in the light shaded area, and greater than 30% in the dark shaded regions. We have found that, over a wide range of parameter space, the branching fractions change abruptly when the nature of the LSP changes. This is demonstrated in Figure 4 by solid contours, where the  $\tilde{\gamma}$ ,  $\tilde{Z}$  and  $\tilde{H}$  symbols on either side of the contours show which component's contribution dominates the LSP. Furthermore we have found that the branching fractions are fairly constant in a given branching region, and approximately  $\text{BF}(\chi_1^0 \rightarrow \tau^\pm + 2jets) \sim 70\%$  in the dark regions, and  $\text{BF}(\chi_1^0 \rightarrow \tau^\pm + 2jets) \sim 15\%$  in the light regions.

It is important to notice that these branching fractions significantly modify the bounds obtained in Ref.[8], where as a first approximation a photino LSP was assumed.

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<sup>8</sup>We are interested in the pair production of sparticles via processes (4) and (5), and the produced selectrons, sneutrinos and squarks will subsequently decay to pairs of LSPs (plus other decay products). The condition that  $\text{BF}(\chi_1^0 \rightarrow \tau^\pm + 2jets) < 30\%$  corresponds to the condition that  $\text{BF}(2\chi_1^0 \rightarrow 1 \text{ or } 2 \tau^\pm s + jets) \lesssim 51\%$ .



### 4.3 LSP Lifetime

In order to get a qualitative understanding of the effects of the neutralino mixing on the LSP lifetime let us consider first a photino LSP. A photino LSP decays within the detector (defined by the decay length  $c\gamma\tau_{LSP}$  being less than  $1m$ ,  $\tau_{LSP}$  is the LSP lifetime) provided [7, 31]

$$\lambda'_{ijk} \geq 3.7\gamma \cdot 10^{-6}(\tilde{m}_f/100\text{ GeV})^2(45\text{ GeV}/M_{LSP})^{5/2} \quad (18)$$

where  $\gamma$  is the Lorentz-boost factor in the laboratory,  $c$  is the speed of light. However, if the LSP is a pure Higgsino, then the decay rate is proportional to the heaviest mass squared normalised to the Higgs vacuum expectation value squared  $2m_i^2/v^2$ , and the corresponding bound on  $\lambda'$  is

$$\lambda'_{ijk} \geq 8.2\gamma \cdot 10^{-5}(m_\tau/(m_i))(\tilde{m}_f/100\text{ GeV})^2(45\text{ GeV}/M_{LSP})^{5/2}. \quad (19)$$

For the  $L_\mu Q_1 \bar{D}_1$  operator, the coupling  $\lambda' \gtrsim 1.4 \cdot 10^{-3}$ , which would still allow a novel region to be explored. For the operator  $L_e Q \bar{D}$  and a Higgsino LSP, the single squark production followed by a direct  $\tilde{R}_p$  decay should be more promising (discussed in [15, 14]). If the LSP does decay outside the detector we are left either with the leptoquark-like signature [16] or the standard missing  $p_T$  signature of the MSSM.

In order to quantify the dependence on the MSSM mixing parameters, we have plotted the regions of parameter space (in black) in Figure 4 for which the LSP (at a value of  $\lambda' = 0.03$ ) decays outside the detector, for an operator  $L_\tau Q \bar{D}$ . These regions coincide with regions where the LSP is dominantly a mixture of Higgsinos/Zinos and the LSP mass is small. This is shown in Figure 5, which plots the LSP lifetime as a function of the Higgsino mass parameter  $\mu$ . The two peaks at  $\mu \sim 0\text{ GeV}$  and  $\mu \sim 100\text{ GeV}$  correspond to the Higgsino/Zino region discussed above. The gap in the middle at  $\mu \sim 50\text{ GeV}$  corresponds to the region where the LSP is not a neutralino. Figure 4 also shows how far the black regions would extend (dashed lines) at the very small values of the coupling constant  $\lambda' = 3 \times 10^{-6}$ .

## 5 Signals and Backgrounds

In order to investigate the full phenomenological consequences of the LSP decay via the  $L_i Q_j \bar{D}_k$  operator, we have used a  $R_p$  violating SUSY generator to simulate the SUSY production mechanism of Figures 1a and 1b and the subsequent  $\tilde{R}_p$  LSP decays at the parton level. Throughout our analysis we have chosen to use the  $MRSD'$  structure function set of reference [32] for the SUSY events and the background samples. We have generated the events at electron and proton beam energies of  $26.6\text{ GeV}$  and  $820\text{ GeV}$  respectively. The SUSY events and potential backgrounds to the SUSY signals were passed through a Monte Carlo detector simulation of the ZEUS experiment based on the GEANT program [33], and subsequently reconstructed using the ZEUS offline programs. We will now proceed to discuss the individual SUSY samples which we have used in our analysis, their signatures, and the potential backgrounds to each of the samples.

## 5.1 SUSY Signals

We have used the MSSM generator [34] to simulate the  $\mathcal{R}_p$  SUSY samples. In order to reduce the large SUSY parameter space, we have made a number of simplifying assumptions in addition to assumptions (A1)-(A3):

- We have assumed sleptons (selectrons and sneutrinos) and the five squarks to be degenerate in mass. Throughout we shall denote the mass of the SUSY scalars as  $M_{SUSY} = m_{\tilde{l}} = m_{\tilde{q}}$ .
- We have only considered one set of gaugino mixing parameters ( $M' = 40 \text{ GeV}$ ,  $\tan(\beta) = 1$  and  $\mu = -200 \text{ GeV}$ ) in the region where the LSP predominantly decays to charged leptons, and one set of parameters ( $M' = 55 \text{ GeV}$ ,  $\tan(\beta)=4$  and  $\mu = +200 \text{ GeV}$ ) in the region where the LSP predominantly decays to neutrinos. As discussed in sections 3 and 4, variations of the gaugino mixing parameters within a given LSP decay region have a relatively small effect on the cross section and LSP branching fractions (we have found that the combined changes in the cross section and the branching fraction are within a factor of two). This is to be compared to the large changes in the cross sections as a function of  $(m_{\tilde{l}} + m_{\tilde{q}})$  which are approximately three orders of magnitudes over the SUSY mass scale of interest to HERA (*cf.* Fig. 2).

We now turn to the signatures of the SUSY events. From the production mechanisms of Figure 1a and 1b two sparticles, a slepton and a squark, are produced. The sleptons and squarks subsequently cascade-decay via processes (13)-(15) to neutralinos. Let us consider two specific examples of events in which the LSP decays via the  $L_\tau Q \bar{D}$  operator (see also Figure 6):

$$e^- + q \rightarrow \tilde{e}^- + \tilde{q} \rightarrow e^- + q + 2\tilde{\chi}_i^0 \rightarrow e^- + q + \tau + \nu_\tau + 4jets. \quad (20)$$

$$e^- + q \rightarrow \tilde{e}^- + \tilde{q} \rightarrow e^- + q + 2\tilde{\chi}_i^0 \rightarrow e^- + q + 2\nu_\tau + 4jets. \quad (21)$$

Processes (20) and (21) are both (NC) processes. Note that the pair of sfermions will eventually cascade-decay to *two* LSPs. Process (20) has a tau in its final state. This can subsequently decay to a positron or a muon via

$$\tau^\pm \rightarrow e^\pm \nu_e \bar{\nu}_\tau (\text{BF} \sim 8.9\%) \quad (22)$$

$$\tau^\pm \rightarrow \mu^\pm \nu_\mu \bar{\nu}_\tau (\text{BF} \sim 17.8\%) \quad (23)$$

and the branching fractions of the decays are shown in brackets. Our overall signals for LSP decays via the  $L_\tau Q \bar{D}$  are thus a positron or a muon and jet activity in the detector. For the  $L_e Q \bar{D}$  and the  $L_\mu Q \bar{D}$  operator, our signals are one or more positrons *or* one or more muons respectively and jet activity in the detector<sup>9</sup>.

Having discussed the signals of interest, we now turn to the generated SUSY samples. We have generated samples of SUSY events for each of the three operators above. The

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<sup>9</sup>Due to the large neutral current deep-inelastic scattering background, the decay of the  $\tau^-$  to an electron is considered a very difficult signature to observe experimentally.

$R_p$ Operator	$M_{SUSY}$ (GeV)	SUSY $M'$ (GeV)	parameters $\tan(\beta)$	$\mu$ (GeV)	Branch (%)	$\sigma_{TOT}$ (pb)	Ngen	Nexp
$L_e Q \bar{D}$	45	40	1	-200	0.80	6.72	940	1344
$L_e Q \bar{D}$	65	40	1	-200	0.80	1.71	500	342
$L_e Q \bar{D}$	80	40	1	-200	0.80	0.50	400	100
$L_e Q \bar{D}$	95	40	1	-200	0.80	0.11	100	22
$L_e Q \bar{D}$	105	40	1	-200	0.80	0.03	100	6
$L_\mu Q \bar{D}$	45	40	1	-200	0.80	10.10	1000	2020
$L_\mu Q \bar{D}$	65	40	1	-200	0.80	2.57	600	514
$L_\mu Q \bar{D}$	80	40	1	-200	0.80	0.75	400	150
$L_\mu Q \bar{D}$	95	40	1	-200	0.80	0.16	400	32
$L_\mu Q \bar{D}$	100	40	1	-200	0.80	0.09	200	18
$L_\tau Q \bar{D}$	45	40	1	-200	0.79	10.09	2000	2018
$L_\tau Q \bar{D}$	65	40	1	-200	0.79	2.56	1000	512
$L_\tau Q \bar{D}$	80	40	1	-200	0.79	0.75	1000	150
$L_\tau Q \bar{D}$	85	40	1	-200	0.79	0.46	400	92
$L_\tau Q \bar{D}$	90	40	1	-200	0.79	0.28	200	56

Table 1: Generated  $R_p$  violating SUSY samples.  $M_{SUSY}$  is the mass of the scalars;  $M'$ ,  $\tan(\beta)$ ,  $\mu$  are the gaugino mixing parameters; Branch is the branching ratio of the LSP to a charged lepton  $BF(\tilde{\chi}_i^0 \rightarrow l^\pm + 2jets)$ ;  $\sigma_{TOT}$  is the total cross section of the sample; Ngen is the number of events generated; Nexp is the number of events expected for an integrated luminosity of  $200\text{pb}^{-1}$ , two nominal years of HERA running.

$L_{e(\mu,\tau)} Q \bar{D}$  sample only contains events in which at least one of the two LSPs has decayed to a positron (muon or tau respectively).

For each type of operator,  $L_e Q \bar{D}$ ,  $L_\mu Q \bar{D}$  and  $L_\tau Q \bar{D}$ , we have generated MC samples at a number of SUSY masses  $M_{SUSY}$  ( $= m_{\tilde{l}} = m_{\tilde{q}}$ ). The samples were generated with the gaugino parameters  $M' = 40\text{ GeV}$ ,  $\tan(\beta)=1$  and  $\mu = -200\text{ GeV}$ , which correspond to a region where the LSP predominantly decays to charged leptons. The diagonalisation of the gaugino mass matrix produces a LSP with a mass of  $M_{LSP} = 44\text{ GeV}$ . Table 1 summarises the SUSY samples, their cross sections and the expected number of events for an integrated luminosity of  $200\text{pb}^{-1}$ .

## 5.2 Backgrounds

The most promising signatures of the  $R_p$  SUSY events are a positron or muon in the final state. Backgrounds to such a signature come from “physics backgrounds”, which produce at least one positron or muon directly, or from “fake backgrounds”, in which either detector effects fake positron or muon signals, or from positrons or muons produced during the fragmentation process from decays of secondary particles. The individual background samples are described below.

In anticipation of a cut in total transverse energy  $E_T$  in the following analysis, and in

Sample Name	Generator	Generated $Q^2$ range ( $\text{GeV}^2$ )	$\sigma_{TOT}(pb)$	Ngen	Nexp
$b\bar{b}$	HERWIG	500→87248	4.506	3395	901.2
$c\bar{c}$	HERWIG	500→87248	37.39	4105	7478
W ( $e^+$ , $\mu$ )	EPVEC	500→87248	0.219	400	43.8
NC	LEPTO	1000→87248	230.0	7149	46000
CC	LEPTO	500→87248	49.5	3541	9900

Table 2: Generated background samples.  $\sigma_{TOT}$  is the total cross section of the sample; Ngen is the number of events generated; Nexp is the number of events expected for an integrated luminosity of  $200\text{pb}^{-1}$ .

order to keep the number of events in our background samples down to a manageable size, we have applied a  $Q^2 > 1000 \text{ GeV}^2$  cut to the deep inelastic scattering neutral current sample, and a  $Q^2 > 500 \text{ GeV}^2$  cut to all other samples at the generator level. Kinematically this corresponds to a cut in total  $E_T$ ,  $E_T > 60 \text{ GeV}$ , and  $E_T > 45 \text{ GeV}$  respectively (see Figure 7). However, because a fraction of the transverse energy in each event will be missed in the detector and also carried off by neutrinos and hence will not be measured, the total visible (or reconstructed) transverse energy will be below the kinematically generated  $E_T$  of Figure 7. Also calorimeter energy resolution effects will broaden the measured  $E_T$  spectrum, and hence smear events in  $E_T$  and shift them to higher/lower values of  $E_T$ . Even taking both effects into account, our generator cuts on  $Q^2$  are well below our final cut of  $E_T > 90 \text{ GeV}$  in the following analysis.

### 5.2.1 Physics Backgrounds

We have considered two types of physics backgrounds. The first one is heavy quark production via high  $Q^2$  photon-gluon fusion [35]. The most dangerous case of photon-gluon fusion is expected to be  $b\bar{b}$  production. The produced  $B^0$  can decay semileptonically to a positron or a muon. We have also considered  $c\bar{c}$  backgrounds, but note that these are generally less dangerous as their  $E_T$  distribution is lower. The HERWIG generator [36] was used to generate  $b\bar{b}$  and  $c\bar{c}$  events. Table 2 summarises all background samples, their cross sections and the expected number of events per luminosity of  $200\text{pb}^{-1}$ , nominally two years of HERA running.

The second physics background considered is W production [37] via the process

$$\gamma^* + q \rightarrow W + q', \quad (24)$$

where the virtual photon is radiated from the electron, and the W can decay to give a positron or a muon. Cross sections are small compared to the photon-gluon fusion backgrounds, but the  $p_T$  of the charged leptons is in general large. The EPVEC generator of reference [37] was used to generate the W sample. The sample only contains events in which the W decays to a positron or a muon.

### 5.2.2 “Fake Backgrounds”

Fake signals of positrons or muons in the ZEUS detector can be caused by a number of effects, and these include

- Misidentification of the curvature (and thus charge) of high  $p_T$  electrons in the tracking detector.
- Hadrons depositing energy in the calorimeter with shower profile characteristics similar to that of a positron (misidentification of positrons in the calorimeter).
- Punch-through of high energetic charged hadrons through the calorimeter will give rise to tracks in the muon chambers, and hence can lead to misidentified muons.

Furthermore, decays of secondary particles produced during fragmentation processes can lead to genuine positrons and muons. In order to investigate all the effects giving rise to fake backgrounds, we have generated deep inelastic neutral current (NC) and charged current (CC) events using the LEPTO program [38]. Table 2 summarises these samples.

## 6 Analysis

### 6.1 Positron and Muon Identification

Positron and muon identification play a key role in the extraction of the SUSY signals. The identification algorithms have to give a high purity in order not to contaminate the search sample with too much fake background. With this in mind, we have chosen the methods below for positron/muon identification.

Positron identification is achieved by first of all finding electromagnetic clusters in the calorimeter, e.g. by finding shower profiles characteristic of those of electrons. We require the cluster to have an energy above  $5\text{ GeV}$ . Tracks in the central drift chamber (CTD) are then extrapolated to the face of the electromagnetic calorimeter. If a track matches such an electron cluster, and the curvature of the track is positive, then the cluster is identified as a positron.

Muon identification is achieved by matching CTD tracks with track segments in the muon chambers. Note however that only high energetic muons can penetrate the calorimeter before they reach the muon chambers which implies an indirect muon momentum cut of  $p_\mu > 3 - 4\text{ GeV}$ .

### 6.2 Cuts

Before we go on to discuss how the SUSY signals can be extracted from the background, we explain the cuts used in the subsequent analysis:

- **“ $e^+$  found and  $\mu$  found”**: positron and muon identification have been discussed in the previous section.

- **“30 GeV < (E − p<sub>z</sub>) < 60 GeV”**:  $E$  is the sum of the total energies of the final state particles measured in the calorimeter, and  $p_z$  is the sum of the z component of momentum<sup>10</sup> of all particles measured in the calorimeter. The  $(E - p_z)$  variable is an important quantity which characterises the event [39]: for e-p events where all final state particles are measured,  $(E - p_z) = 2E_e$ , where  $E_e$  is the energy of the initial state electron. Undetected particles which are emitted down the forward beampipe give a negligible loss in  $(E - p_z)$ , while for example photoproduction (i.e.  $\gamma$ -p scattering) processes in which the scattered electron remains in the beampipe, predominantly result in low values of  $(E - p_z)$ . The  $(E - p_z)$  cut is very efficient in rejecting photoproduction events and other backgrounds to the deep inelastic scattering processes of interest.

In our study we have used the  $(E - p_z)$  cut to mainly reject charged current (CC) events and W events. In both types of background a considerable fraction of the energy is carried off by neutrinos, and hence will not be detected. As a result the  $(E - p_z)$  distribution of such events is shifted towards lower values.

- **“circularity > 1”**: One can define a 2-dimensional-like sphericity, circularity [40], which is defined in the range  $0 < \text{circularity} < 1$ . The circularity (transverse sphericity) is defined by

$$\text{circularity} = 2\lambda_2 \quad (25)$$

in terms of the smaller eigenvalue,  $\lambda_2$ , of the two dimensional sphericity tensor

$$S_{\alpha\beta} = \sum_i p_{i\alpha} p_{i\beta} / \sum_i p_i^2 \quad (26)$$

where  $\alpha, \beta$  are Cartesian components,  $i$  runs over the number of particles (i.e. reconstructed calorimeter clusters) in the event, and  $p$  are the four-momenta of the particles. The circularity reflects the isotropy of the event. A circularity of unity corresponds to a completely isotropic event. A three jet event, for example, with the three jets pointing in directions of the azimuthal angle,  $\phi$ ,  $\phi = 0^\circ$ ,  $\phi = 120^\circ$  and  $\phi = 240^\circ$  would be a good example of an event with a high value of circularity. A two jet event, with a back-to-back jet configuration has a circularity close to zero. We shall use this cut to distinguish between the SUSY events and backgrounds. As will be discussed below, the SUSY events are very isotropic, and thus have a high value of circularity.

- **“ $E_T > 90$  GeV”**:  $E_T$  is the total transverse energy measured in the calorimeter. We also include the measurement of the muon track in the  $E_T$  if a muon was found.

### 6.3 Signal Extraction

We first examine the characteristics of the positrons and muons in the events. Figure 8a and 8b show the muon and positron  $p_T$  spectra for the SUSY samples at  $M_{SUSY} =$

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<sup>10</sup>The z-axis is defined to point along the proton direction.

80 GeV, correctly normalised with respect to each other. Note that the muon and positron  $p_T$  spectrum of the  $L_\tau Q \bar{D}$  sample is much softer than the  $L_\mu Q \bar{D}$  and  $L_e Q \bar{D}$   $p_T$  spectra. This is because the  $\tau$ 's have to decay via processes (22) and (23) to positrons and muons, and hence the energy of the  $e^+$  or  $\mu$  is shared with the associated neutrinos.

Even though the  $p_T$  spectrum of the  $L_\mu Q \bar{D}$  sample is slightly harder than the  $p_T$  spectrum of the backgrounds of section 5.2, we conclude that the positron or muon  $p_T$  variable is not a good discriminator between the SUSY signals and the background processes.

Next we consider the circularity of the events. The decay process (20) gives a typical SUSY event topology, consisting of 5 jets, a  $\tau$  lepton, an electron, neutrinos and the proton remnant. Unfortunately not all of the jets are well resolved - most of the jets will generally be very soft. We have found that jet finding algorithms can wrongly recombine the softer jets with harder jets, and the jet multiplicity of such events can be incorrectly determined. We have run jet-finders on the MC samples, and have found that the jet multiplicity *can* be used to discriminate between the SUSY events and backgrounds. However, we have also found that the circularity variable is vastly superior to jet multiplicity. This can be explained as follows:

- The high number of jets result in a more isotropic event structure for the SUSY events. This makes the events more circular than their respective backgrounds.
- Soft jets can not be resolved by jet-finders, but they do contribute to the circularity of the event.

Figure 9 shows the circularity of all combined backgrounds and the SUSY  $L_\tau Q \bar{D}$  samples with  $M_{SUSY} = 45 \text{ GeV}$  and  $M_{SUSY} = 80 \text{ GeV}$ . We observe two features:

- The circularity of the background falls off much more rapidly than the circularity of the SUSY events, therefore a cut in circularity (chosen to be at 0.1) will be a good discriminator between the SUSY signal and background.
- Higher SUSY scalar masses have the effect of making the events more circular - as a result higher  $M_{SUSY}$  samples will be more efficient in passing the circularity cut.

Figure 10a shows the  $E_T$  distribution of the backgrounds with and without a circularity cut. The cut reduces the background by a factor of 10 at  $E_T = 60 \text{ GeV}$ , and by a factor of 18 at  $E_T = 140 \text{ GeV}$ . A similar plot is shown for the SUSY  $L_\tau Q \bar{D}$  samples with SUSY masses  $M_{SUSY} = 45 \text{ GeV}$  and  $M_{SUSY} = 80 \text{ GeV}$ . Again note that for the higher mass sample the efficiency of the number of events surviving the circularity cut at large values of  $E_T$  is higher than for the lower mass sample.

After requiring an  $e^+$  or  $\mu$  and applying  $(E - p_z)$  and circularity cuts to the MC background samples, we are left with  $(102.4 \pm 20.9)$  events. Figure 11a shows their  $E_T$  distribution. The right-hand side of the  $E_T$  tail is dominated by  $b\bar{b}$  and  $c\bar{c}$  events. Note that due to the higher cross section the  $c\bar{c}$  sample is predominant in the  $E_T$  background distribution up to an  $E_T$  of 80 GeV. The background events with  $E_T > 80 \text{ GeV}$  are all  $b\bar{b}$  events, which generally have a much harder  $E_T$  spectrum. We have chosen our

final cut at  $E_T > 90 \text{ GeV}$ . This includes  $(0.53 \pm 0.31) \text{ } b\bar{b}$  events. Figure 11b shows for comparison the  $E_T$  distributions of the three SUSY samples  $L_e Q \bar{D}$ ,  $L_\mu Q \bar{D}$  and  $L_\tau Q \bar{D}$  at high mass ranges.

## 6.4 Discovery Reaches

We now apply the analysis described above to all MC samples. The only difference in the cut sequence applied to the  $L_e Q \bar{D}$ , the  $L_\mu Q \bar{D}$  and the  $L_\tau Q \bar{D}$  samples is the positron/muon selection. We demand

- One or more found positrons for the  $L_e Q \bar{D}$  sample.
- One or more found muons for the  $L_\mu Q \bar{D}$  sample.
- One or more found positrons *or* muons for the  $L_\tau Q \bar{D}$  sample.

Tables 3, 4 and 5 show the effects of the cuts on the SUSY samples and the backgrounds. Figure 12a shows the efficiencies of the samples after cuts. Normalising the cross sections of table 1 to an integrated luminosity of  $L=200\text{pb}^{-1}$ , and folding in the efficiencies of Figure 12a we obtain Figure 12b. We then use Poisson statistics to investigate the potential discovery limit of the  $L_e Q \bar{D}$  operator at the 90% confidence level, by requiring at least 2.3 signal events and assuming zero background. The above condition holds over the SUSY mass range  $90 \text{ GeV} < (m_{\tilde{l}} + m_{\tilde{q}}) < 205 \text{ GeV}$  for the  $L_e Q \bar{D}$  operator and the chosen set of gaugino parameters ( $M' = 40 \text{ GeV}$ ,  $\tan(\beta)=1$  and  $\mu = -200 \text{ GeV}$ ). The lower mass point at  $(m_{\tilde{l}} + m_{\tilde{q}}) = 90 \text{ GeV}$  corresponds to the current model-independent LEP bounds. Using the same argument for the  $L_\mu Q \bar{D}$  and the  $L_\tau Q \bar{D}$  sample, but requiring at least 3.1 signal events and assuming 0.53 background events we can determine the approximate 90%CL discovery reaches for the  $L_\mu Q \bar{D}$  and the  $L_\tau Q \bar{D}$  operators. Note that the gaugino parameters of the above SUSY MC samples were chosen in a region where the LSP predominantly decays to charged leptons.

We have also investigated a region in SUSY parameter space where the LSP predominantly decays to neutrinos. Table 6 lists the SUSY cross sections and LSP branching ratios in this region. Because the parameters  $M' = 55 \text{ GeV}$ ,  $\tan(\beta)=4$  and  $\mu = +200 \text{ GeV}$  produce a LSP with  $M_{LSP} = 44 \text{ GeV}$ , the same LSP mass as the generated MC samples of table 1, we can use the efficiencies of Figure 12a to obtain the expected number of events after cuts of Figure 12c.

Using the criteria previously described we now summarise the maximum discovery reaches for the three operators  $L_e Q \bar{D}$ ,  $L_\mu Q \bar{D}$  and  $L_\tau Q \bar{D}$  in the two regions of gaugino parameter space:

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 205 \text{ GeV for dominant } L_e Q \bar{D}, \text{ LSP decays to } e^\pm, \quad (27)$$

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 185 \text{ GeV for dominant } L_e Q \bar{D}, \text{ LSP decays to } \nu_{e^\pm}, \quad (28)$$

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 195 \text{ GeV for dominant } L_\mu Q \bar{D}, \text{ LSP decays to } \mu^\pm, \quad (29)$$

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 175 \text{ GeV for dominant } L_\mu Q \bar{D}, \text{ LSP decays to } \nu_{\mu^\pm}, \quad (30)$$

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 170 \text{ GeV for dominant } L_\tau Q \bar{D}, \text{ LSP decays to } \tau^\pm, \quad (31)$$

$$m(\tilde{e}, \tilde{\nu}) + m(\tilde{q}) \lesssim 140 \text{ GeV for dominant } L_\tau Q \bar{D}, \text{ LSP decays to } \nu_{\tau^\pm}. \quad (32)$$



cut	$b\bar{b}$	$c\bar{c}$	W	NC	CC
none	3395	4105	400	7149	3541
$e^+$ found	22	24	118	55	8
$30\text{ GeV} < (E - p_z) < 60\text{ GeV}$	20	21	27	54	2
circularity $> 0.1$	4	7	9	5	0
$E_T > 90\text{ GeV}$	0	0	0	0	0
Exp. no. of evts	0	0	0	0	0

cut	$L_e Q \bar{D}_{45}$	$L_e Q \bar{D}_{65}$	$L_e Q \bar{D}_{80}$	$L_e Q \bar{D}_{95}$	$L_e Q \bar{D}_{105}$
none	940	500	400	100	100
$e^+$ found	423	230	177	38	44
$30\text{ GeV} < (E - p_z) < 60\text{ GeV}$	385	201	151	35	36
circularity $> 0.1$	255	174	136	33	33
$E_T > 90\text{ GeV}$	67	124	124	32	32
Exp. no. of evts	$95 \pm 10$	$84.5 \pm 6.5$	$31.0 \pm 2.3$	$7.0 \pm 1.0$	$1.9 \pm 0.3$

Table 3: The cut-sequence applied to the MC samples. Here “ $L_e Q \bar{D}_{45}$ ” refers to the SUSY sample with  $M_{SUSY} = 45\text{ GeV}$ , and LSP decays via the  $L_e Q \bar{D}$  operator. The last row shows the expected number of events, properly normalised, after cuts for an integrated luminosity of  $200\text{ pb}^{-1}$ .

cut	$b\bar{b}$	$c\bar{c}$	W	NC	CC
none	3395	4105	400	7149	3541
$\mu$ found	126	71	65	29	11
$30\text{ GeV} < (E - p_z) < 60\text{ GeV}$	114	59	24	20	3
circularity $> 0.1$	42	18	3	2	0
$E_T > 90\text{ GeV}$	2	0	0	0	0
Exp. no. of evts	$0.53 \pm 0.31$	0	0	0	0

cut	$L_\mu Q \bar{D}_{45}$	$L_\mu Q \bar{D}_{65}$	$L_\mu Q \bar{D}_{80}$	$L_\mu Q \bar{D}_{95}$	$L_\mu Q \bar{D}_{100}$
none	1000	600	400	400	200
$\mu$ found	395	191	114	119	50
$30\text{ GeV} < (E - p_z) < 60\text{ GeV}$	330	157	92	102	44
circularity $> 0.1$	177	131	78	88	31
$E_T > 90\text{ GeV}$	27	71	58	79	31
Exp. no. of evts	$54 \pm 10$	$60.7 \pm 6.7$	$21.8 \pm 2.7$	$6.3 \pm 0.6$	$2.8 \pm 0.5$

Table 4: The cut-sequence applied to the MC samples. Here “ $L_\mu Q \bar{D}_{45}$ ” refers to the SUSY sample with  $M_{SUSY} = 45\text{ GeV}$ , and LSP decays via the  $L_\mu Q \bar{D}$  operator.

cut	$b\bar{b}$	$c\bar{c}$	W	NC	CC
none	3395	4105	400	7149	3541
$e^+$ or $\mu$ found	148	95	183	84	19
$30 \text{ GeV} < (E - p_z) < 60 \text{ GeV}$	134	80	51	74	5
circularity $> 0.1$	46	25	12	7	0
$E_T > 90 \text{ GeV}$	2	0	0	0	0
Exp. no. of evts	$0.53 \pm 0.31$	0	0	0	0

cut	$L_\tau Q \bar{D}_{45}$	$L_\tau Q \bar{D}_{65}$	$L_\tau Q \bar{D}_{80}$	$L_\tau Q \bar{D}_{85}$	$L_\tau Q \bar{D}_{90}$
none	2000	1000	1000	400	200
$\mu$ found	185	74	92	33	14
$30 \text{ GeV} < (E - p_z) < 60 \text{ GeV}$	166	53	71	27	11
circularity $> 0.1$	105	40	58	21	8
$E_T > 90 \text{ GeV}$	17	26	44	17	8
Exp. no. of evts	$17.2 \pm 4.2$	$13.4 \pm 2.6$	$6.6 \pm 0.9$	$3.9 \pm 0.9$	$2.2 \pm 0.8$

Table 5: The cut-sequence applied to the MC samples. Here “ $L_\tau Q \bar{D}_{45}$ ” refers to the SUSY sample with  $M_{SUSY} = 45 \text{ GeV}$ , and LSP decays via the  $L_\tau Q \bar{D}$  operator.

$R_p$ Operator	SUSY parameters				Branch (%)	$\sigma_{TOT}$ (pb)
	$M_{SUSY}$ (GeV)	$M'$ (GeV)	$\tan(\beta)$	$\mu$ (GeV)		
$L_e Q \bar{D}$	45	55	4	+200	0.16	1.67
$L_e Q \bar{D}$	65	55	4	+200	0.16	0.43
$L_e Q \bar{D}$	80	55	4	+200	0.16	0.12
$L_e Q \bar{D}$	95	55	4	+200	0.16	0.03
$L_e Q \bar{D}$	105	55	4	+200	0.16	0.01
$L_\mu Q \bar{D}$	45	55	4	+200	0.16	3.12
$L_\mu Q \bar{D}$	65	55	4	+200	0.16	0.81
$L_\mu Q \bar{D}$	80	55	4	+200	0.16	0.24
$L_\mu Q \bar{D}$	95	55	4	+200	0.16	0.05
$L_\mu Q \bar{D}$	100	55	4	+200	0.16	0.03
$L_\tau Q \bar{D}$	45	55	4	+200	0.16	3.12
$L_\tau Q \bar{D}$	65	55	4	+200	0.16	0.81
$L_\tau Q \bar{D}$	80	55	4	+200	0.16	0.24
$L_\tau Q \bar{D}$	85	55	4	+200	0.16	0.15
$L_\tau Q \bar{D}$	90	55	4	+200	0.16	0.09

Table 6: Generated  $R_p$  violating SUSY samples in a region of gaugino parameter space where the LSP predominantly decays to neutrinos.

Note that the discovery reaches (27)-(32) only hold for the assumptions we have made in section 5.1, and only for the particular choice of the gaugino mixing parameters, namely ( $M' = 40 \text{ GeV}$ ,  $\tan(\beta)=1$  and  $\mu = -200 \text{ GeV}$ ) for dominant LSP decays to  $l^\pm$ , and ( $M' = 55 \text{ GeV}$ ,  $\tan(\beta)=4$  and  $\mu = +200 \text{ GeV}$ ) for dominant LSP decays to  $\nu_{l^\pm}$ . We have also investigated the effect of smaller LSP masses on the detection efficiencies of the samples, but found that they are generally small: for a LSP mass of  $M_{LSP} = 20 \text{ GeV}$  the correction to the efficiencies of Figure 12a (at  $M_{LSP} = 44 \text{ GeV}$ ) were found to be approximately greater than 0.6. Furthermore, because cross section variations as a function of  $M'$ ,  $\tan(\beta)$  and  $\mu$  are relatively small (see section 3) and changes in the LSP branching fractions to charged leptons are fairly constant in a given characteristic region of the LSP (see section 4) we conclude that the discovery reaches of (27)-(32) are approximately valid over a wide range of gaugino mixing parameter space within a given characteristic region of the LSP.

## 7 Discussion and Conclusions

We have investigated decays of the LSP as a general neutralino via the  $LQ\bar{D}$  operator. We have found that the results depend on the mixing parameters of the neutralinos. Three distinct regions in the parameter space characterise the LSP decay: (1) A region in which the photino component of the LSP is dominant. In this region branching fractions to charged leptons are high, typically  $\sim 70\%$ . (2) A region in which the zino component of the LSP is dominant. In this region branching fractions to charged leptons are low, and typically  $\sim 15\%$ . (3) A region in which the LSP is dominantly a Higgsino/Zino admixture at low LSP masses. In this region the decay rate of the LSP can become so small that the LSP only decays within the detector for anomalously large couplings  $\lambda'$ , in which case the only distinguishing feature of  $\mathcal{R}_p$  is the single sfermion production. In all other cases the LSP decays in the detector for  $\mathcal{R}_p$  Yukawa couplings as low as  $10^{-3}$ . At couplings  $\lambda' = 3 \cdot 10^{-6}$  the LSP decays inside the detector in only half the mixing scenarios.

Based on the above results we have investigated the discovery reaches of HERA on the  $LQ\bar{D}$  operator using a full MC simulation of pair produced SUSY signals with subsequent  $\mathcal{R}_p$  decays of the LSP. We have considered the regions (1) and (2) of Section 4.2 in gaugino parameter space, and have found that  $\mathcal{R}_p$  SUSY can be discovered at HERA up to combined SUSY masses ( $m(\tilde{e}, \tilde{\nu}) + m(\tilde{q})$ ) of

- $170 \text{ GeV}$ ,  $195 \text{ GeV}$ ,  $205 \text{ GeV}$  for  $L_\tau Q\bar{D}$ ,  $L_\mu Q\bar{D}$ ,  $L_e Q\bar{D}$  and mixing scenario (1)
- $140 \text{ GeV}$ ,  $175 \text{ GeV}$ ,  $185 \text{ GeV}$  for  $L_\tau Q\bar{D}$ ,  $L_\mu Q\bar{D}$ ,  $L_e Q\bar{D}$  and mixing scenario (2)

after two years of HERA running at nominal luminosity. The discovery reaches are to be compared with existing limits of  $90 \text{ GeV}$ ,  $145 \text{ GeV}$ ,  $145 \text{ GeV}$  ( $L_\tau Q\bar{D}$ ,  $L_\mu Q\bar{D}$ ,  $L_e Q\bar{D}$ ). The limits will only hold for the investigated LSP mixing scenarios and for the set of assumptions we have made on the SUSY model, namely that (a) the LSP is a neutralino, that (b) only one of the 27 operators  $L_i Q_j \bar{D}_k$  is dominant, that (c) sleptons and squarks are degenerate in mass, and that (d) the branching fraction of sfermion cascade decays to the LSP is 100%.

Because HERA is an inherently cleaner environment than the Tevatron, there are clear advantages for the search of  $\mathcal{R}_p$  SUSY signals. Firstly our analysis demands only one charged lepton from one of the LSP decays. Consequently future limits from HERA will be less model dependent, and thus complimentary to existing limits from the Tevatron<sup>11</sup>. Secondly our analysis is sensitive to LSP decays to  $\tau$ 's. HERA is the first collider experiment which can directly probe the  $L_\tau Q \bar{D}$ . The discovery potential of  $\tau$  signals at HERA nicely ties in with existing model independent limits on sfermion masses from LEP and proposed searches for  $\tau$  signals at LEP 200.

We conclude that HERA offers a very promising discovery potential for direct searches for  $\mathcal{R}_p$  SUSY, which is nearly twice as high as the existing indirect bounds on the  $L_\tau Q \bar{D}$  operator.

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## Appendix

Here we complete the discussion on the LSP decay matrix element. The relevant coupling constants are given in Table 7. Here  $a(p_i)$  denotes the coupling to the Higgsino which is proportional to the mass, and  $b(p_i)$  is the coupling to the gauginos.  $N(1), N(2)$  are the LSP admixtures of the Bino and the neutral Wino respectively.  $N(3), N(4)$  are the Higgsino admixtures.

The matrix element squared for decay via the baryon number violating operator (which we do not make use of in this paper) is given by.

$$\begin{aligned}
|\mathcal{M}(\tilde{\chi}_0 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k)|^2 &= 8c_f g^2 \lambda'^2 \{ \\
&D(\tilde{u}_i)^2 \bar{d}_j \cdot \bar{d}_k \quad [(b(u)^2 + a(u_1)^2) \tilde{\chi}_0 \cdot \bar{u}_i - 2b(u)a(u_i)m_{u_i}M_{\tilde{\chi}_0}] \\
&+ D(\tilde{d}_j)^2 \bar{u}_i \cdot \bar{d}_k \quad [(a(d_j)^2 + b(d)^2) \tilde{\chi}_0 \cdot \bar{d}_j - 2b(d)a(d_j)m_{d_j}M_{\tilde{\chi}_0}] \\
&+ D(\tilde{d}_k)^2 \bar{u}_i \cdot \bar{d}_j \quad [(a(\bar{d}_k)^2 + b(\bar{d})^2) \tilde{\chi}_0 \cdot \bar{d}_k - 2b(\bar{d})a(\bar{d}_k)m_{d_k}M_{\tilde{\chi}_0}] \\
&+ D(\tilde{u}_i)D(\tilde{d}_k) \quad [a(\bar{u}_i)a(\bar{d}_j)g(\bar{u}_i, \tilde{\chi}_0, \bar{d}_j, \bar{d}_k) + b(\bar{u})b(\bar{d})m_{u_i}m_{d_k}\tilde{\chi}_0 \cdot \bar{d}_k \\
&\quad - b(\bar{u})a(\bar{d}_j)m_{u_i}M_{\tilde{\chi}_0}\bar{d}_j \cdot \bar{d}_k - b(\bar{d})a(\bar{u}_i)m_{d_j}M_{\tilde{\chi}_0}\bar{u}_i \cdot \bar{d}_k] \\
&+ D(\tilde{u}_i)D(\tilde{d}_j) \quad [a(\bar{u}_i)a(\bar{d}_k)g(u_i, \tilde{\chi}_0, d_k, d_j) + b(\bar{u})b(\bar{d})m_{u_i}m_{d_k}\tilde{\chi}_0 \cdot \bar{d}_j \\
&\quad - b(\bar{u})a(\bar{d}_k)m_{u_i}M_{\tilde{\chi}_0}\bar{d}_j \cdot \bar{d}_k - b(\bar{d})a(\bar{u}_i)m_{d_k}M_{\tilde{\chi}_0}\bar{u}_i \cdot \bar{d}_j] \\
&+ D(\tilde{d}_j)D(\tilde{d}_k) \quad [a(\bar{d}_j)a(\bar{d}_k)g(d_j, \tilde{\chi}_0, d_k, u_i) + b(\bar{d})b(\bar{d})m_{d_j}m_{d_k}\tilde{\chi}_0 \cdot \bar{u}_i \\
&\quad - b(\bar{d})a(\bar{d}_k)m_{d_j}M_{\tilde{\chi}_0}\bar{u}_i \cdot \bar{d}_k - b(\bar{d})a(\bar{d}_j)m_{d_k}M_{\tilde{\chi}_0}\bar{u}_i \cdot \bar{d}_j] \}
\end{aligned} \tag{33}$$

The notation is as in Section 4.1. The colour factor  $c_f = 6$ .

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<sup>11</sup>The analysis of reference [8] assumes *dilepton* signals coming from the  $\mathcal{R}_p$  decay of two LSPs.

	$a(p_i)$	$b(p_i)$
$e_i$	$\frac{N(3)}{2M_W \cos \beta} m_{e_i}$	$-\frac{1}{2}(N(2) + \tan \theta_W N(1))$
$\bar{e}_i$	$\frac{N(3)}{2M_W \cos \beta} m_{e_i}$	$-\tan \theta_W N(1)$
$\nu_i$	0	$\frac{1}{2}(N(2) - \tan \theta_W N(1))$
$u_i$	$\frac{N(4)}{2M_W \sin \beta} m_{u_j}$	$\frac{1}{2}(N(2) + 1./3. \tan \theta_W N(1))$
$\bar{u}_i$	$\frac{N(4)}{2M_W \sin \beta} m_{u_j}$	$\frac{2}{3} \tan \theta_W N(1)$
$d_i$	$\frac{N(3)}{2M_W \cos \beta} m_{d_k}$	$-\frac{1}{2}(N(2) - \frac{1}{3} \tan \theta_W N(1))$
$\bar{d}_i$	$\frac{N(3)}{2M_W \cos \beta} m_{d_k}$	$-\frac{1}{3} \tan \theta_W N(1)$

Table 7: The Coupling constants  $a(p_i)$  and  $b(p)$  used in the LSP decay calculation.

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Figure 1:

Figure 2:

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Figure 10:

Figure 11:

Figure 12:



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